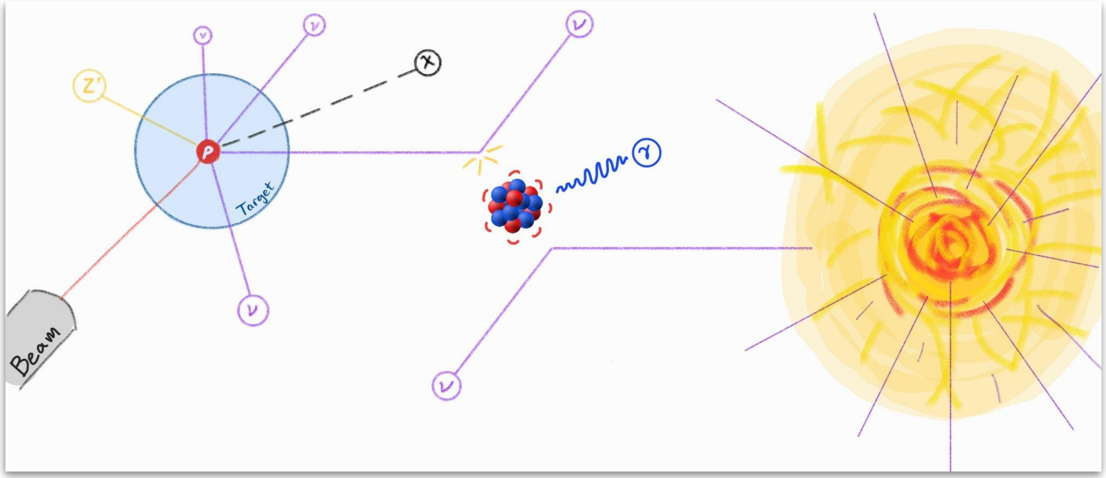
CEvNS with reactor neutrinos (and more)

INT workshop April 2023

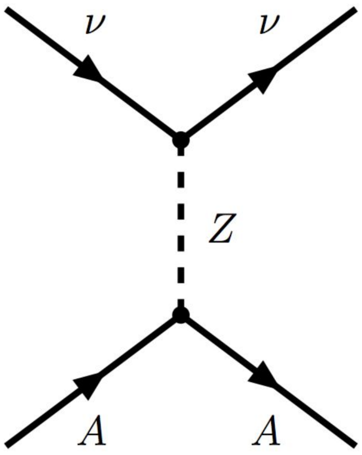


Jayden L. Newstead
The University of Melbourne

Collaborators:
Wei-Chih Huang, Bhaskar Dutta (Texas A&M),
Vishvas Pandey (Fermilab)

A brief history of CEvNS

Coherent
Elastic
ν (neutrino)
Nucleus
Scattering



$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}(E_r, E_\nu) = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

$$Q_W = \mathcal{N} - (1 - 4\sin^2\theta_W)\mathcal{Z}$$

1959
-1967
Glashow-Weinberg-Salam formulate electroweak theory

1973
Gargamelle observes weak neutral currents (neutrino-hadronic)

1977
Freedman – coherent neutral currents

1983
Discovery of the Z-boson

2017
First observation by COHERENT

Potential neutrino sources for CEvNS

1. Solar neutrinos
2. Geo neutrinos
3. Reactors
4. Supernovae
5. Stopped pion
6. Atmospheric neutrinos (?)

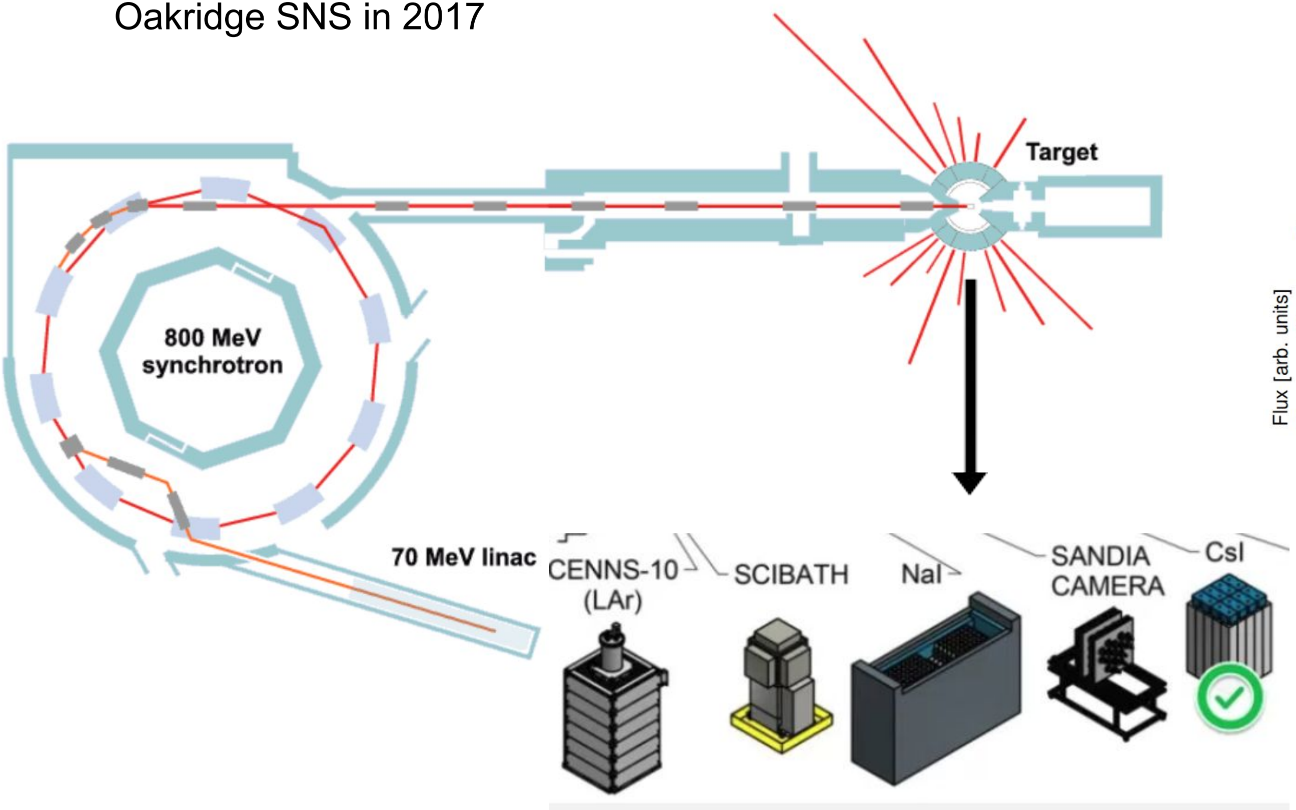
Increasing Energy

CEvNS experiments

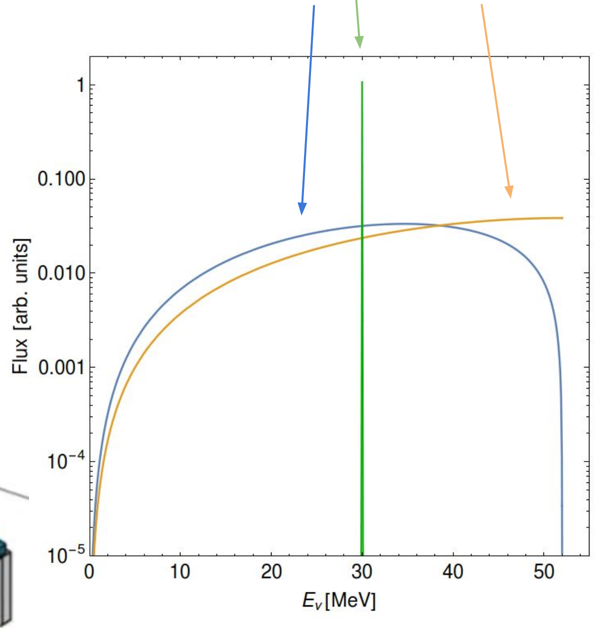
Experiment	Source	Detector	Status
COHERENT	Stopped pion (SNS)	CsI, LAr, NaI, Ge	Running
CCM	Stopped pion (Lujan)	LAr	Running
BULLKID	Reactor	Si (KIDS)	R&D
CONNIE	Reactor (Argentina)	Si (Skipper CCD)	Running
CONUS	Reactor (Germany)	Ge (cryogenic)	Running
MINER	Reactor (USA)	Ge, Si, Sapphire (cryo)	*Looking for new reactor*
NEON	Reactor (S. Korea)	NaI	Running
NEWS-G3	Reactor	Xe, Ar, Ne, He	R&D
NUCLEUS	Reactor (France)	CaWO4 (cryogenic)	Building
RICOCHET	Reactor (France)	Ge (cryogenic) and Zn	Building
TEXONO	Reactor (Taiwan)	Ge (point contact)	Running

CEvNS discovery at the SNS

First observed by the COHERENT collaboration at the Oakridge SNS in 2017



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



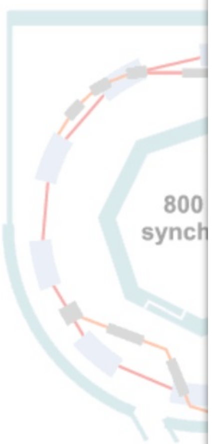
Flux ~ 10^{15} ν/s

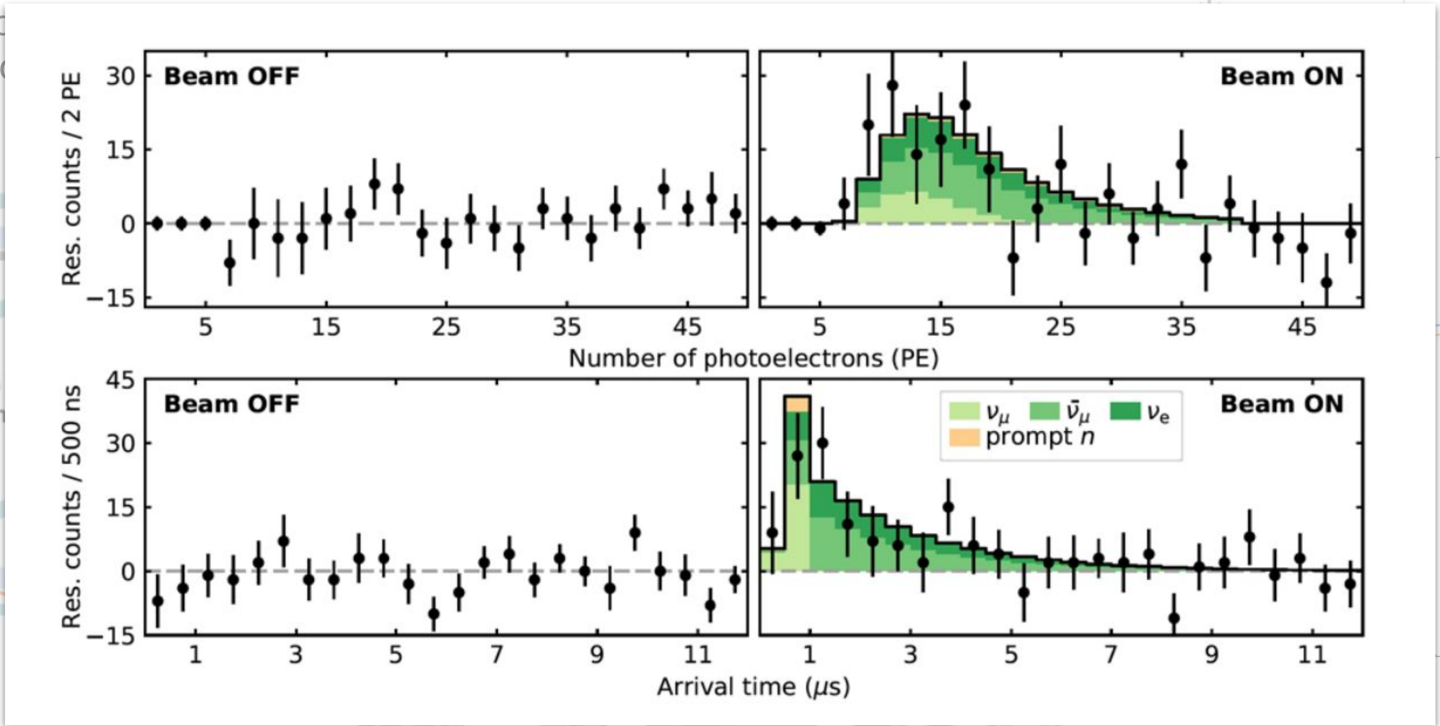
CEvNS discovery at the SNS

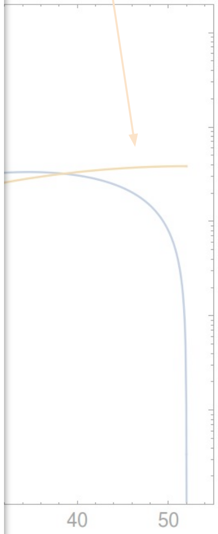
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$+ \ \bar{\nu}_\mu$

First c
Oakri





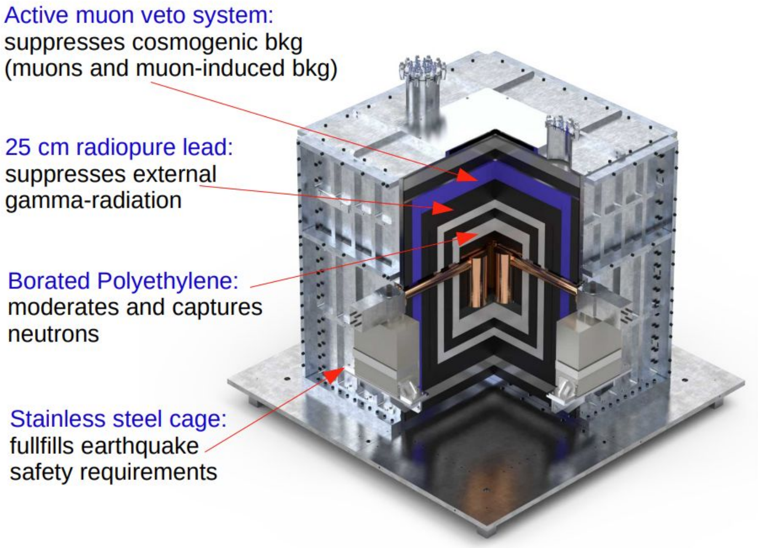


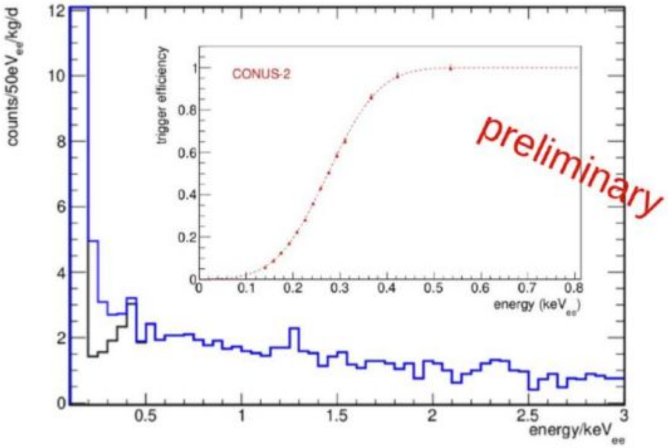
Akimov et al.
Science Vol. 357, 6356 (2017)

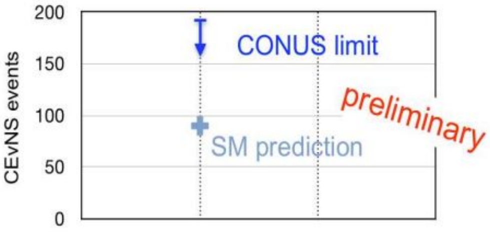
Best fit of: 134±22 CNS events
Implying: 77±16% of SM cross section

CEvNS discovery at reactors?

CONUS are likely the closest:

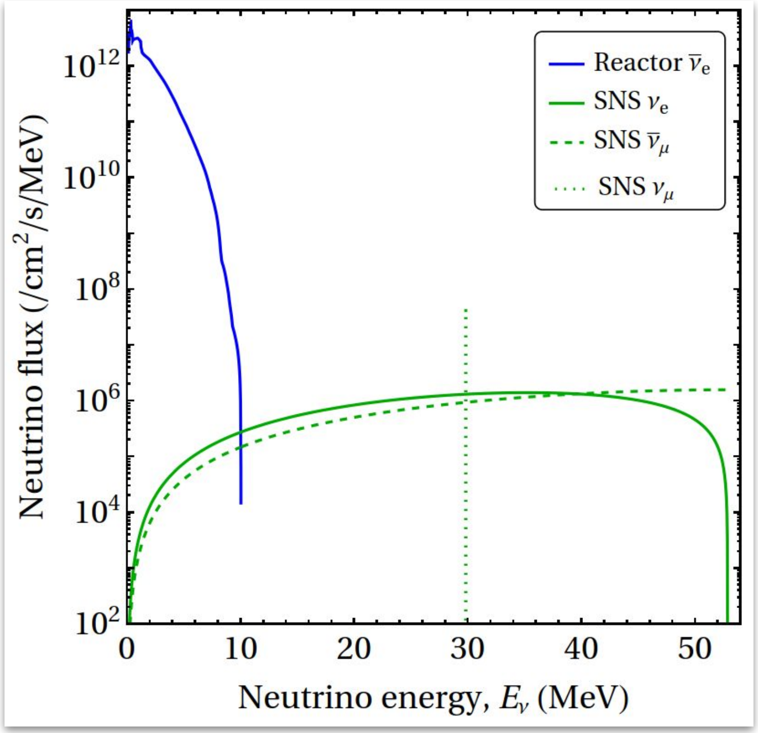


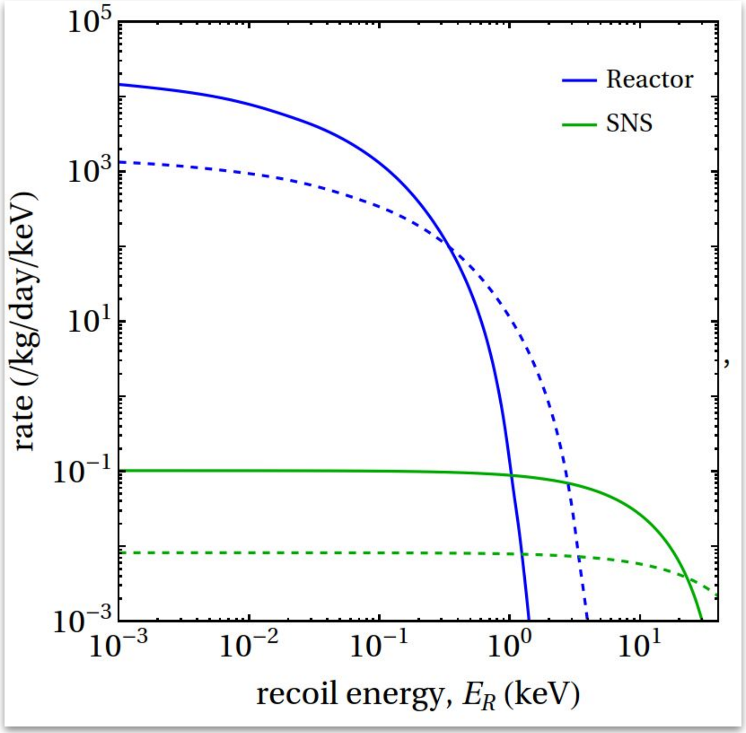




From Werner Maneschg, Magnificent CEvNS 2023

CEvNS from reactors is tough





Solid: xenon, dashed: argon, no quenching

Migdal rate calculation

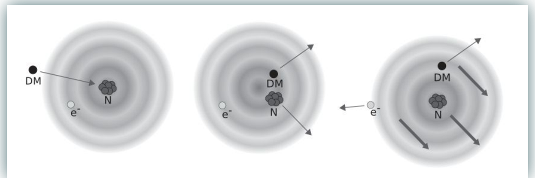
- What goes into the rate calculation?

$$\frac{d^2R}{dE_{\rm NR}dE_i} = \frac{d^2R_{iT}}{dE_{\rm NR}dE_i} \times |Z_{\rm ion}|^2$$

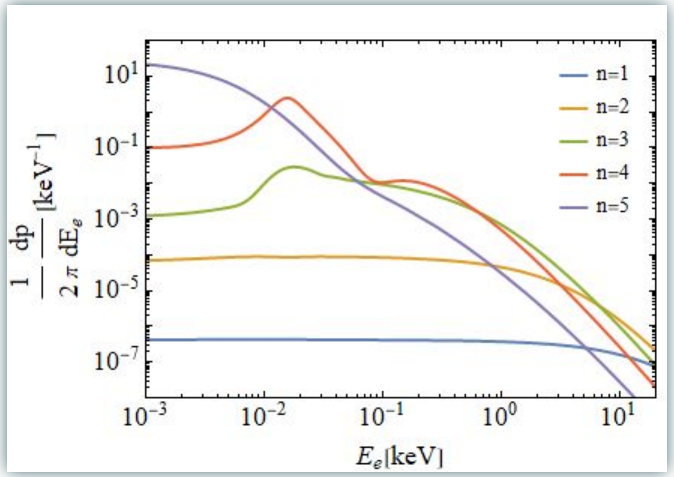
$$|Z_{\rm ion}|^2 = \frac{1}{2\pi}\sum_{n,\ell}\int dE_e \frac{d}{dE_e} p^c_{q_e}(n\ell \to (E_e))$$

- What does such an event look like?

$$E_{\rm det} = \mathcal{L}E_R + E_e + E_{nl}$$



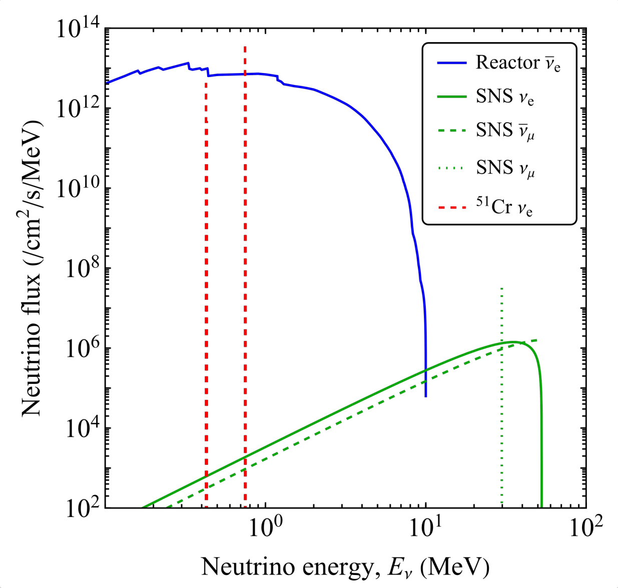
Dolan et al. PRL 2017

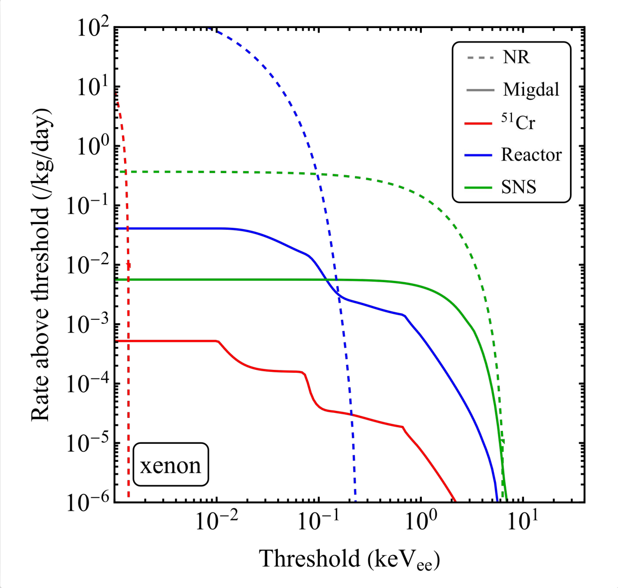


M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, arXiv:1707.07258

Low-energy neutrino sources

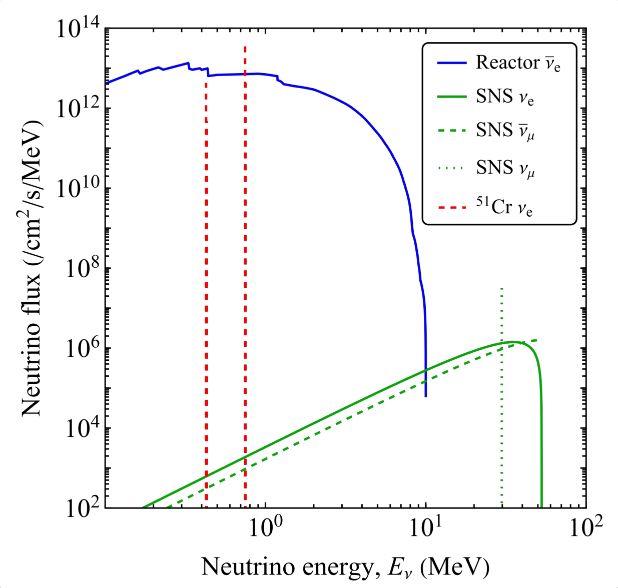
source	flux ($/cm^2/s$)	max E_ν (MeV)	max E_R^{Xe} (keV)
nuclear reactor	1.5×10^{13}	10	1.7
SNS	4.2×10^{6}	52.8	47
^{51}Cr	4.8×10^{13}	0.746	0.01

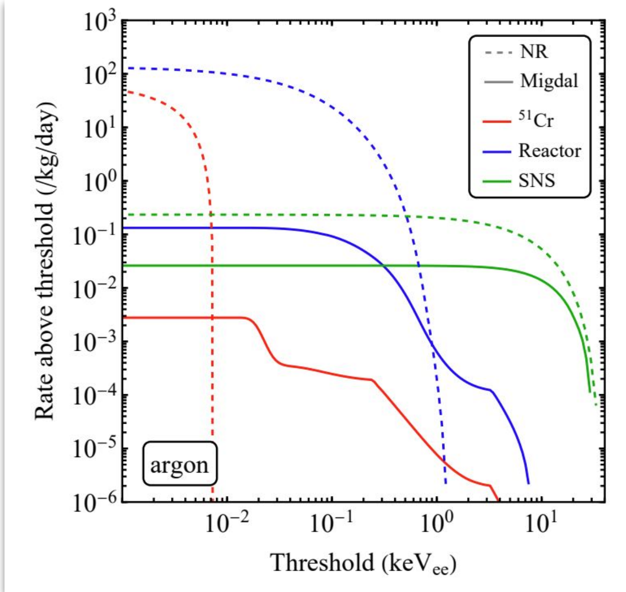




Low-energy neutrino sources

source	flux (/cm^2/s)	max E_ν (MeV)	max E_R^{Xe} (keV)
nuclear reactor	1.5×10^{13}	10	1.7
SNS	4.2×10^{6}	52.8	47
^{51}Cr	4.8×10^{13}	0.746	0.01

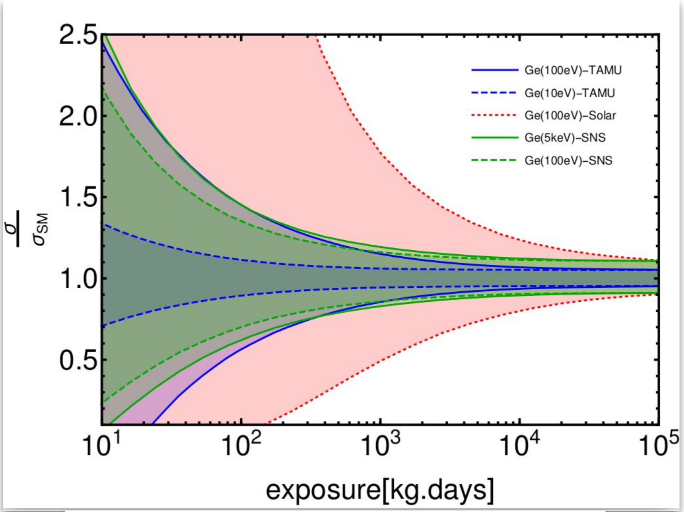


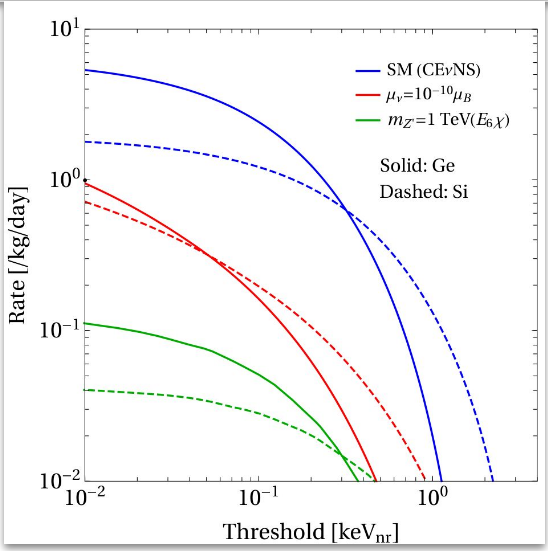


Beyond discovering CEvNS

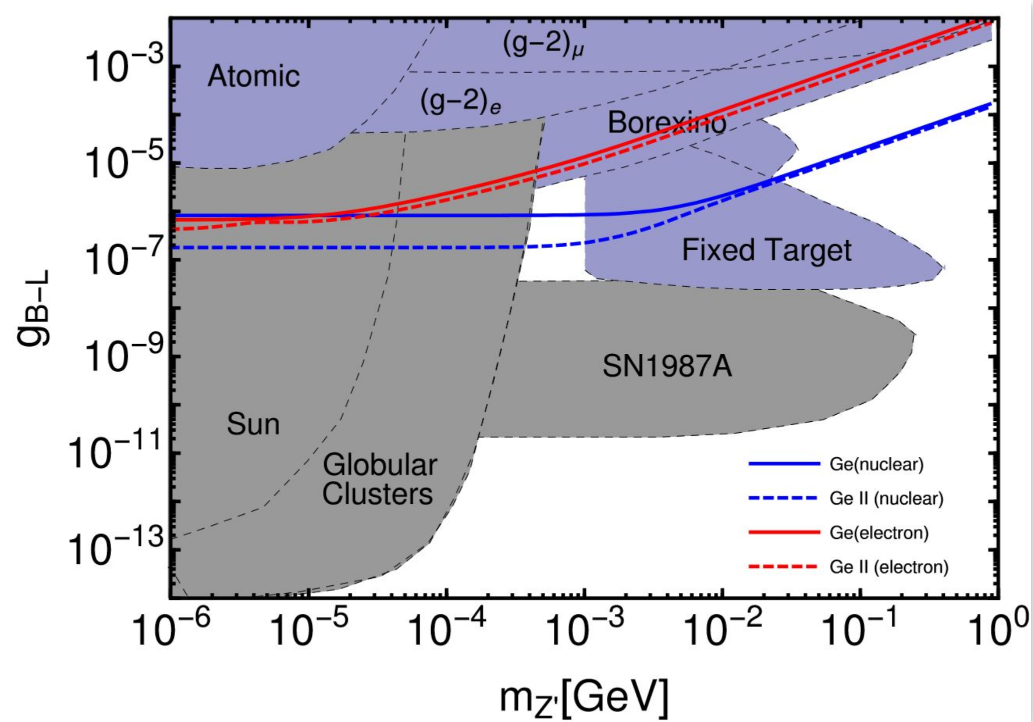
What is it good for?

- Low energy $\sin\theta_w$ measurement
- Study nuclear form factors
- Reactor flux measurements
- Astrophysical processes (SN)
- Sterile search
- BSM searches





Modified neutrino interactions (!NSI)



Consider a $U(1)_{B-L}$ with light Z'

Exclusion limit after exposure
8,000 kg.days
@ 20m from 1GW reactor

JLN, Dutta, Dent, Strigari, Liao, Walker
arXiv:1612.06350

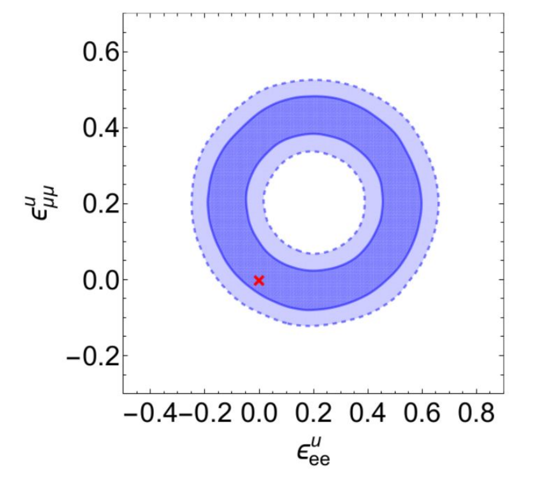
Complementarity of sources and detectors when constraining NSI

- Bayesian priors:

Parameter	Prior range	Scale
$\epsilon^f_{\alpha\alpha}$	(-1.5, 1.5)	linear
SNS flux	$(4.29 \pm 0.43) \times 10^9$	Gaussian
Reactor flux	$(1.50 \pm 0.03) \times 10^{12}$	Gaussian
SNS background	$(5 \pm 0.25) \times 10^{-3}$	Gaussian
Reactor background	(1 ± 0.1)	Gaussian

- Experimental configurations:

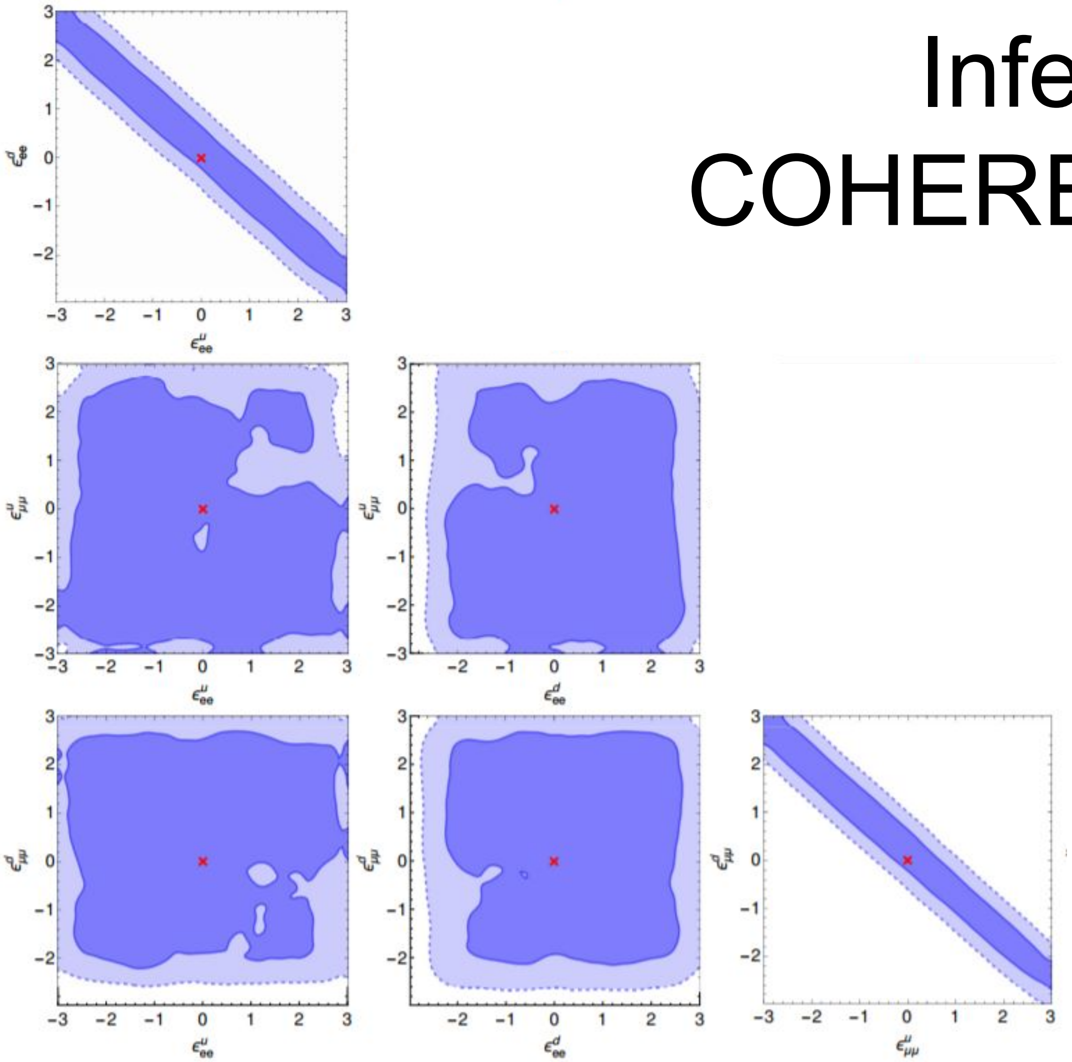
Name	Detector	Source	Exposure	Threshold
Current (COHERENT)	CsI	SNS (20m)	4466 kg.days	4.25 keV
Future (reactor)	Ge	1GW reactor (20m)	10^4 kg.days	100 eV
	Si	1GW reactor (20m)	10^4 kg.days	100 eV
Future (accelerator)	NaI	SNS (20m)	1 tonne.year	2 keV
	Ar	SNS (20m)	1 tonne.year	30 keV



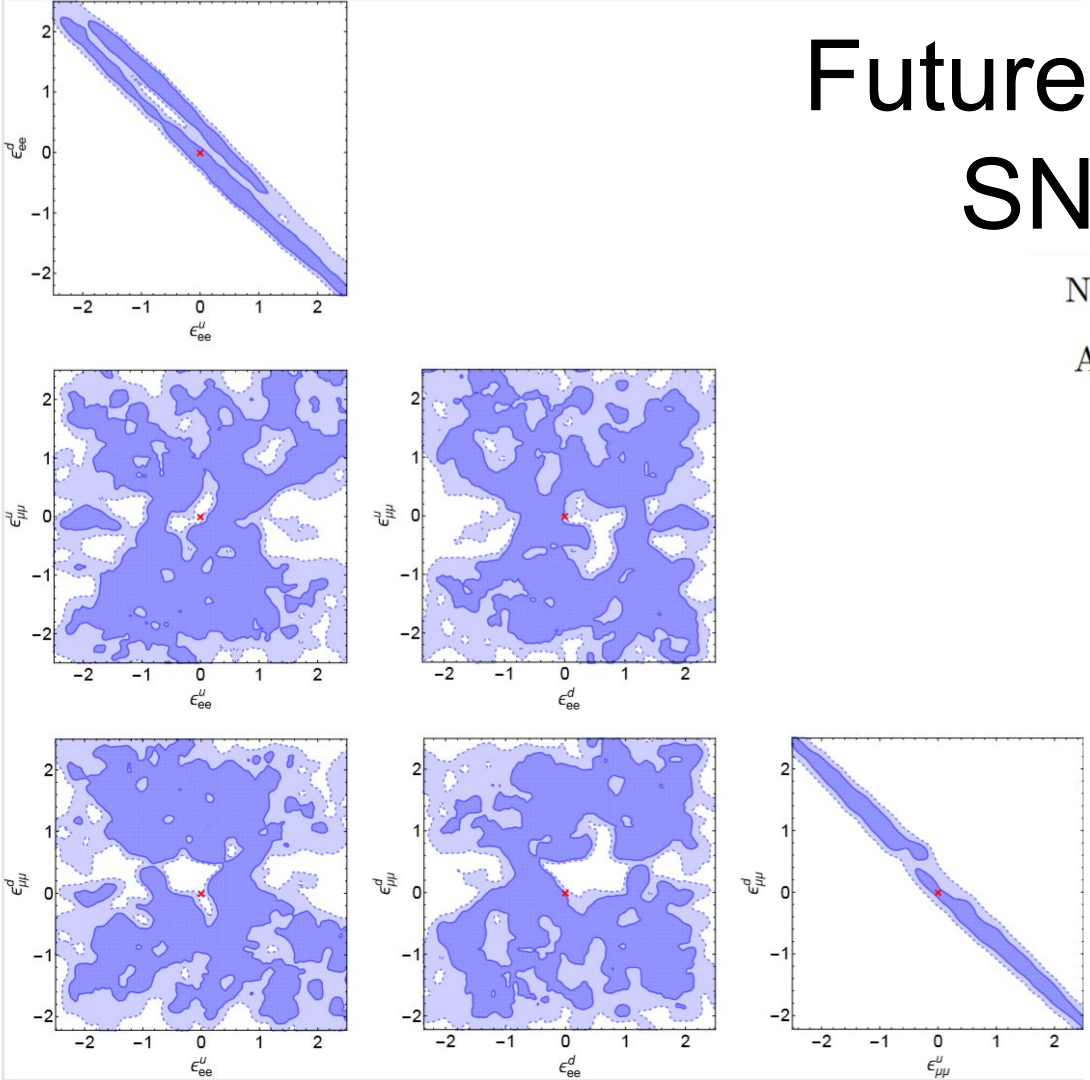
JLN, Dutta, Dent, Liao, Strigari, Walker
arXiv:1711.03521

Inference for COHERENT 2017 data

4466 kg.days CsI only



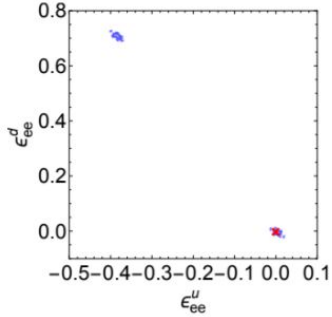
JLN, Dutta, Dent, Liao, Strigari, Walker
arXiv:1711.03521



Future Inference SNS only

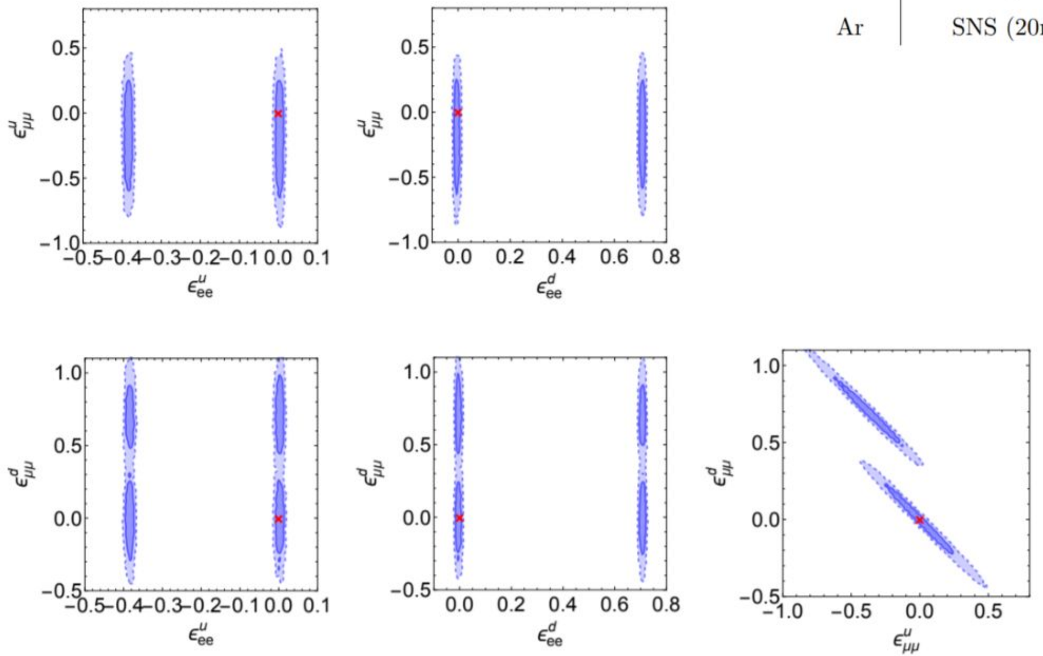
NaI	SNS (20m)	1 tonne.year
Ar	SNS (20m)	1 tonne.year

JLN, Dutta, Dent, Liao, Strigari, Walker
arXiv:1711.03521



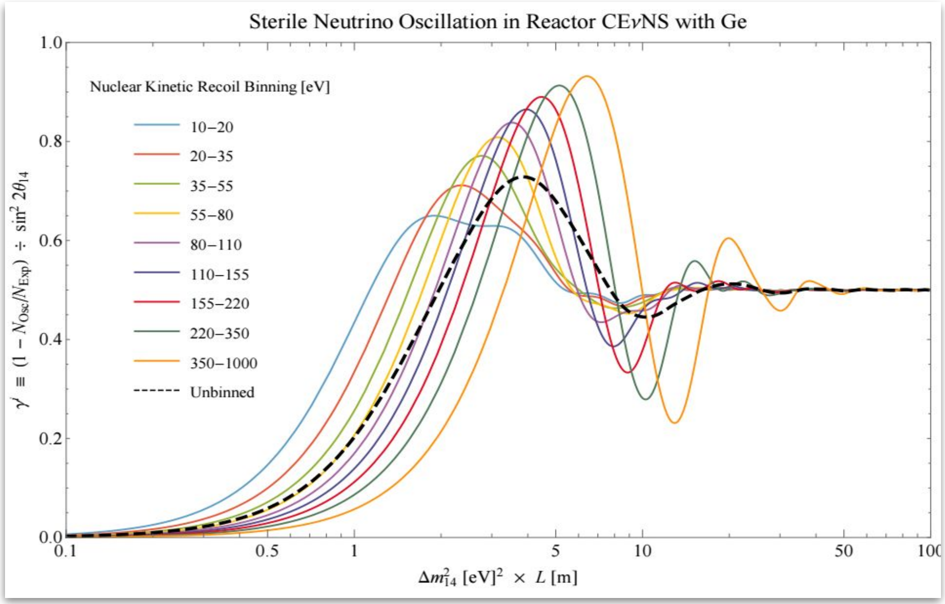
Future Inference with Reactor + Accelerator

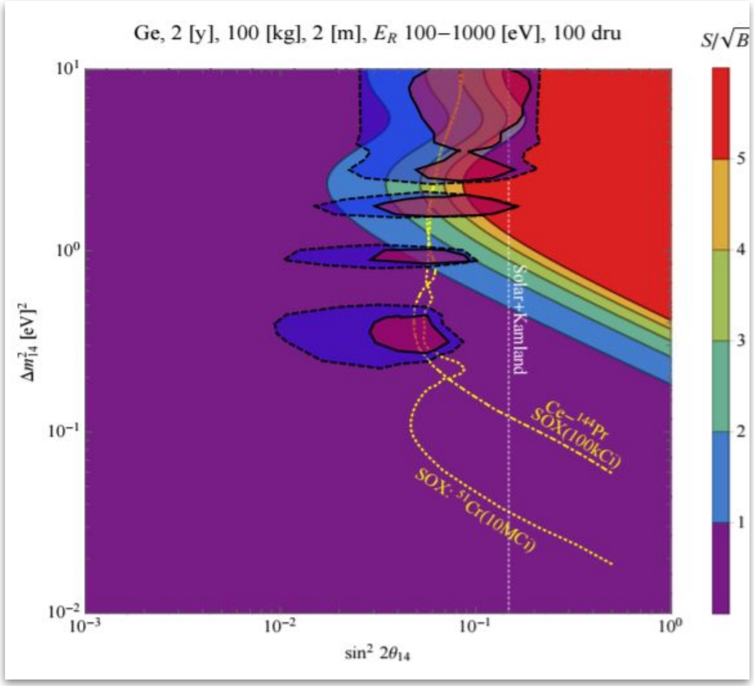
Ge	1GW reactor (20m)	10^4 kg.days
Si	1GW reactor (20m)	10^4 kg.days
NaI	SNS (20m)	1 tonne.year
Ar	SNS (20m)	1 tonne.year



JLN, Dutta, Dent, Liao, Strigari, Walker
arXiv:1711.03521

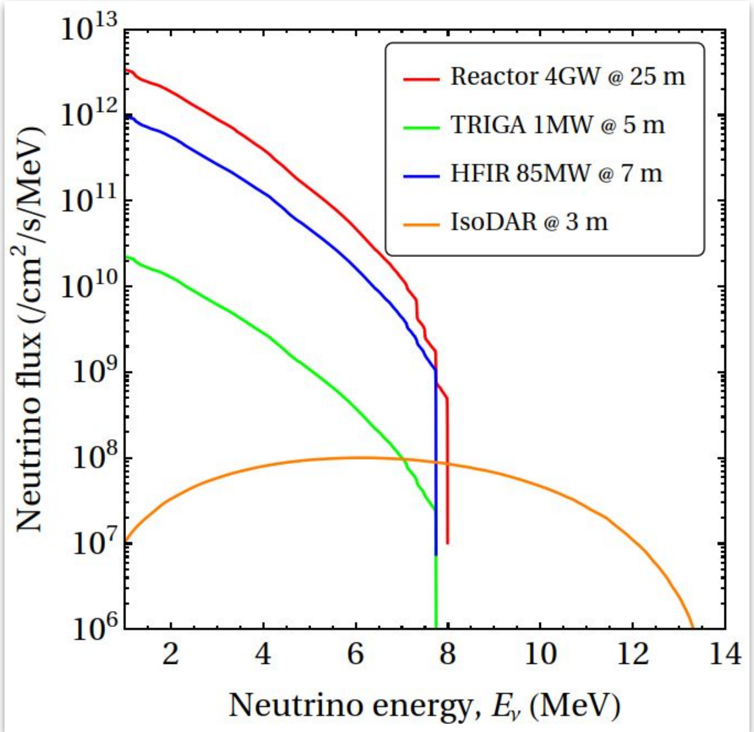
Sterile neutrino oscillations with reactors

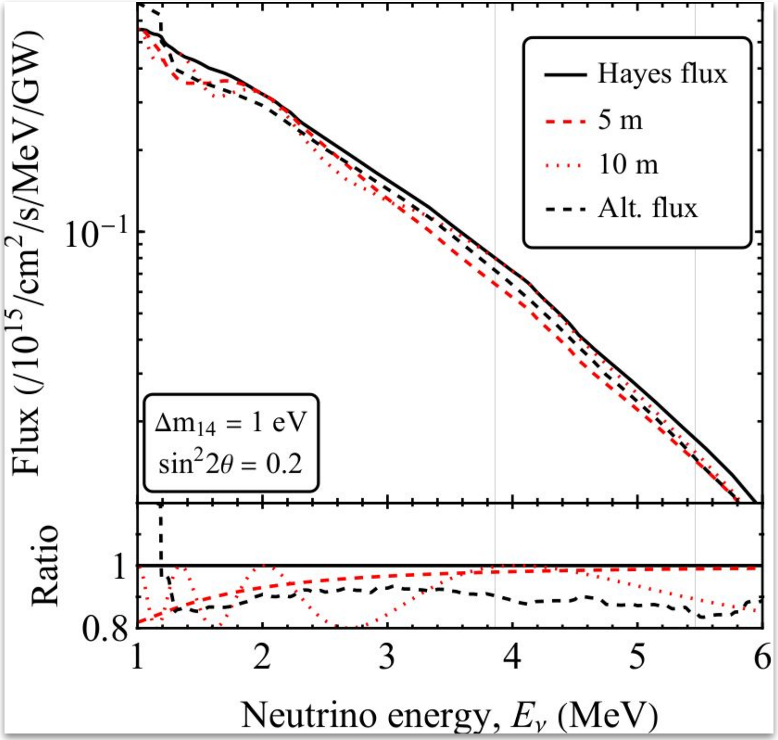




Dutta, Gao, Kubik, Mahapatra, Mirabolfath, Strigari, Walker arXiv:1511.02834

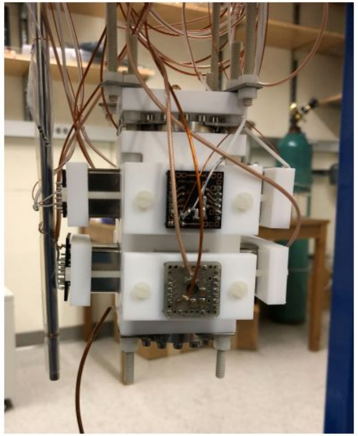
Sterile neutrino oscillations with reactors

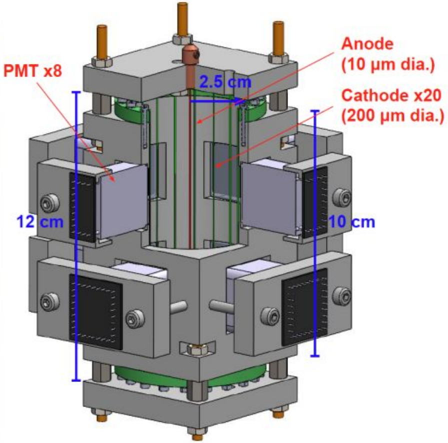




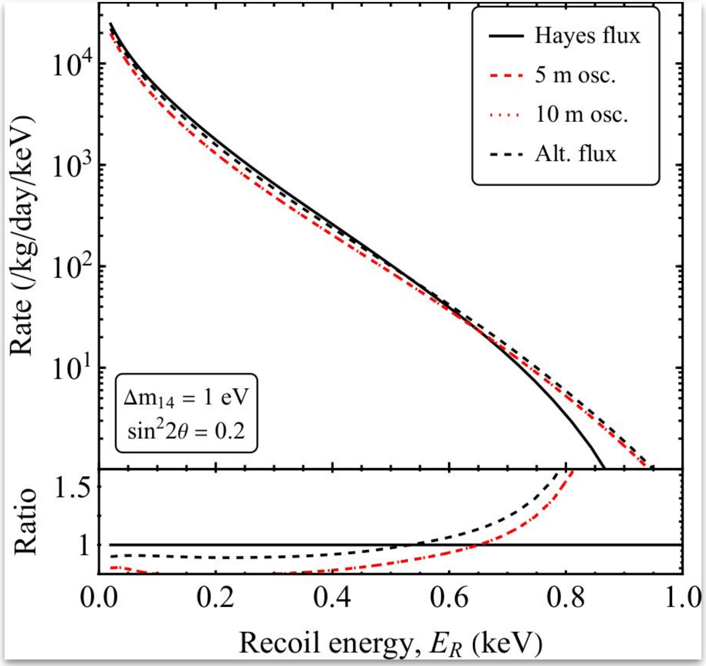
Sterile neutrino oscillations with CEvNS

New xenon detector designed for low threshold



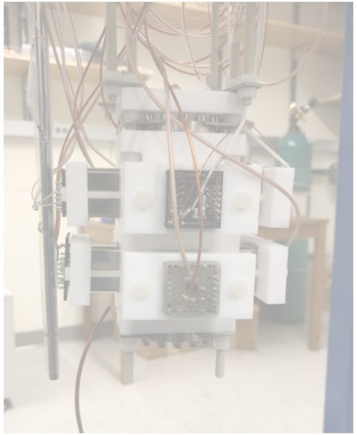


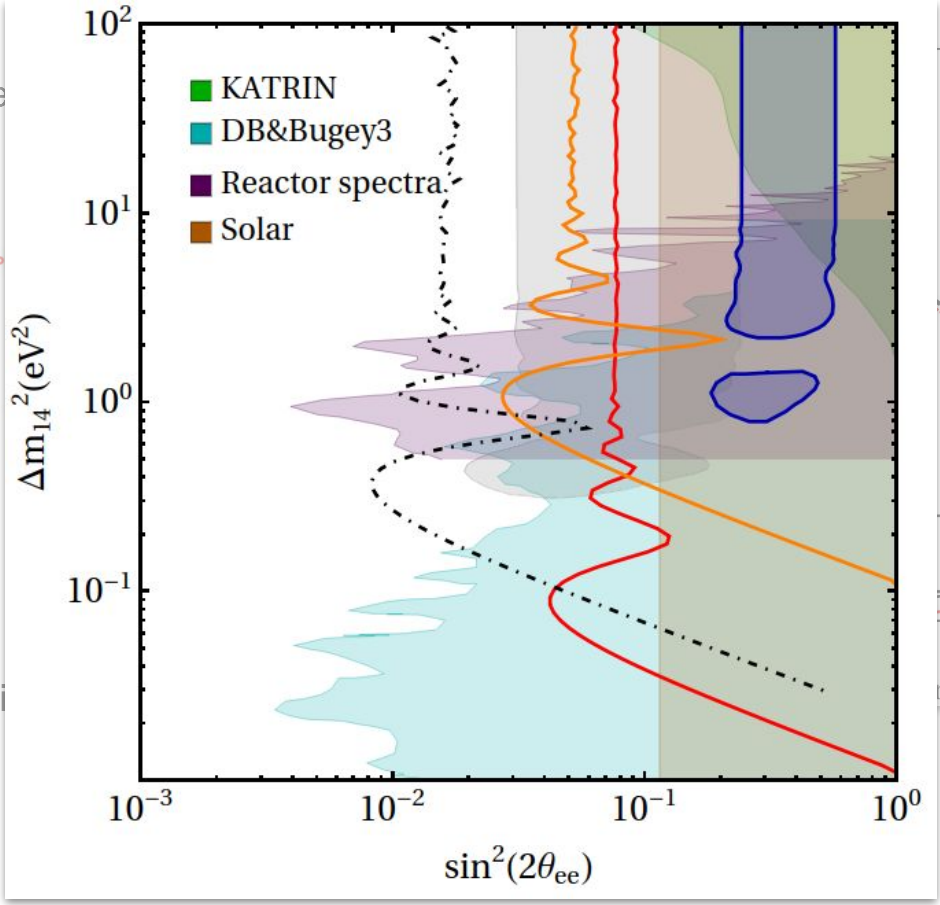
K. Ni et al. arXiv:2301.12296

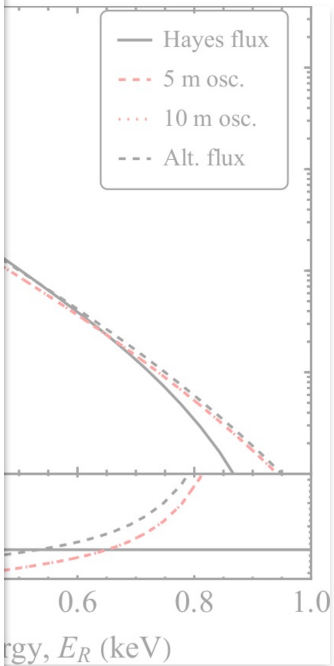


Sterile neutrino oscillations with CEvNS

New xenon detector de



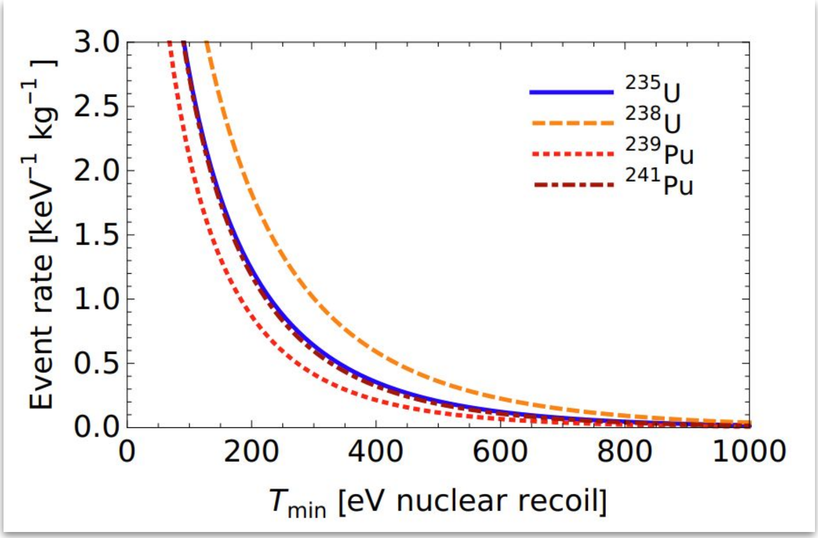


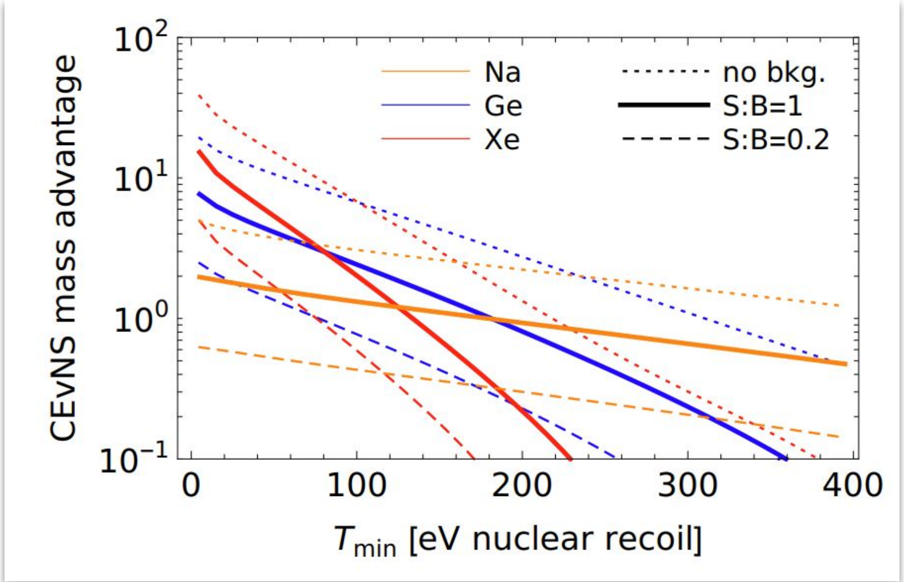


K. Ni et al. arXi

Reactor monitoring with CEvNS

- Monitoring the power and/or fuel content of reactors from stand-off distances

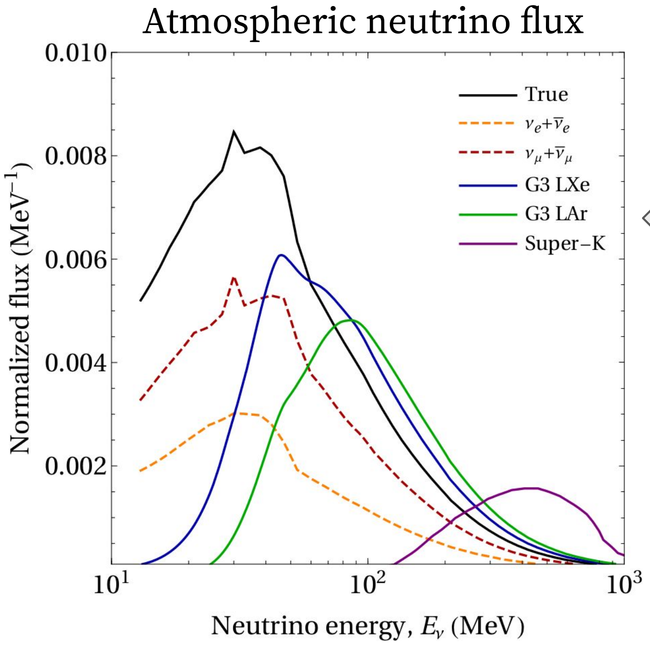




M. Bowen, P. Huber arXiv:2005.10907

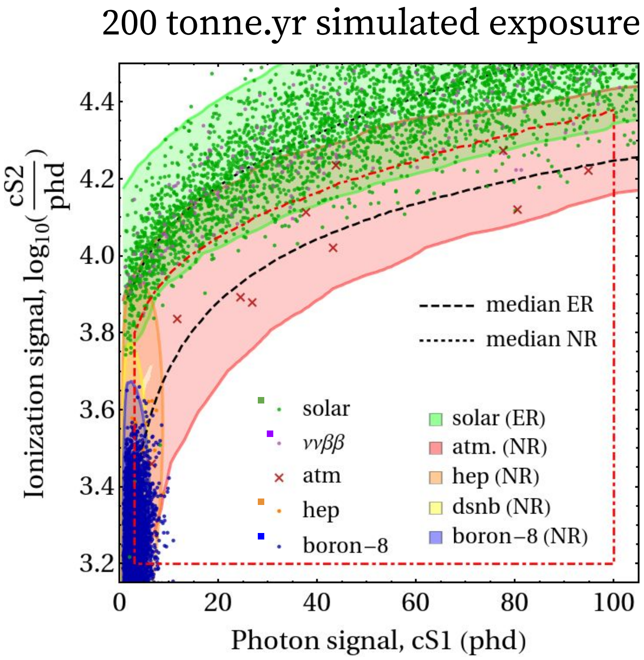
Atmospheric neutrinos in a G3 LXe detector

- The atmospheric flux has not been measured below 100 MeV
- Coherent elastic neutrino-nucleus scattering (CEvNS) can very low thresholds
- A 100t fiducial LXe detector was simulated using NEST (g1 = 0.3 phd/γ, g2 = 112 phd/e).



Distribution of neutrino energies that various detectors are sensitive to

Regions showing 95% CI of the various neutrino sources/channels

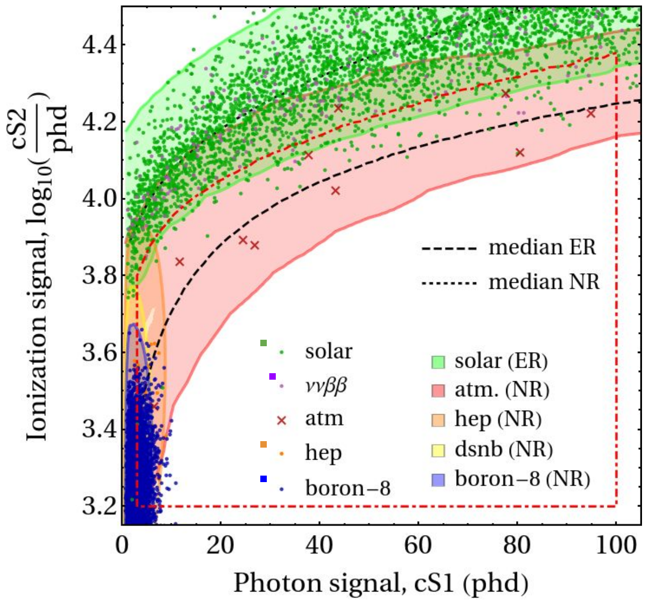


JLN, R. Lang, L. Strigari arxiv:2002.08566

Atmospheric neutrinos in a G3 LXe detector

- CEvNS of atmospheric neutrinos have a rate of 0.06 per tonne per year (0.05 after 95% ER cut)
- Electron recoils due to solar neutrinos have a rate ~1/tonne/year (after 95% ER cut)
- What exposure would be required to (re)discover atmospheric neutrinos?

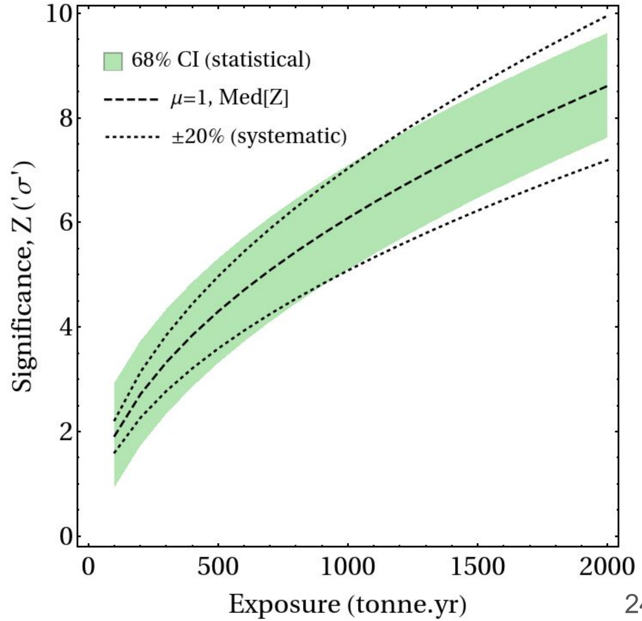
200 tonne.yr simulated exposure



A 100t fiducial detector was simulated using NEST (g1 = 0.3 phd/γ, g2 = 112 phd/e). Shaded regions show 95%

A binned analysis with Asimov data was carried out in the ROI (90% ER cut defined by the red dot-dashed) to find the expected significance

Atm. ν discovery in Xenon (g_1=0.3)



JLN, R. Lang, L. Strigari arxiv:2002.08566

Conclusions

- While CEvNS at reactors is tough, it will soon be observed
- There is a large flux for those with small enough thresholds
- Reactors help break degeneracies in stopped-pion only constraints
- A search for steriles is plausible and would provide an ‘independent’ measurement with different systematics
- Atmospheric neutrinos would be difficult to observe, need huge exposures